Proceedings of ICAD2014
The Eighth International Conference on Axiomatic Design
Campus de Caparica – September 24-26, 2014
ICAD-2014-26

COUPLING AND COMPLEXITY IN ADDITIVE MANUFACTURING PROCESSES

Mary Kathryn Thompson
mkath@mek.dtu.dk
Department of Mechanical Engineering
Technical University of Denmark
Produktionstorvet Bldg. 425
2800 Kgs. Lyngby
Denmark

Joseph Timothy Foley
foley@ru.is
Department of Science and Engineering
Reykjavík University
Menntavegur 1
Reykjavík 101
Iceland

ABSTRACT

This work analyzes and compares traditional subtractive machining processes (milling and turning) and additive manufacturing processes (fused deposition modeling, selective sintering, stereolithography, and 3D printing) in an Axiomatic Design context. The processes are examined from a local and isothermal perspective then as time-varying systems to determine the degree of coupling and time-dependent complexity they exhibit. It is shown that subtractive processes exhibit more coupling within the design matrix than additive manufacturing processes. However, additive processes are intrinsically coupled at the voxel level and seem to exhibit more time-dependent complexity than their subtractive counterparts.

Keywords: additive manufacturing, machining, coupling, complexity.

1 INTRODUCTION

In recent years, additive manufacturing has been hailed as a "wonder technology" [Mishra, 2013] that will eliminate the need for Design for Manufacturing [Tucker, 2013] and bring about the "third industrial revolution" [Markillie, 2012]. While such statements could be dismissed as pure sensationalism, they hint at an interesting hypothesis: additive manufacturing uncouples the artifact ('what we want to achieve') from its production ('how we want to achieve it'). If this were true, these technologies would represent ideal manufacturing processes from the perspective of Axiomatic Design Theory [Suh, 1990; Suh, 2001] and Suh's [2005] Complexity Theory.

In this work, we analyze and compare common traditional subtractive machining processes (milling and turning) and additive manufacturing processes (fused deposition modeling, selective sintering, stereolithography, and 3D printing). In the first part of the paper, each process is viewed from the perspective of a discrete operation: the individual cut or the creation of an individual voxel (or unit volume) of new material. This allows variations in time and temperature to be neglected, and simplifies the decompositions and design matrices. In the second part of the paper, each process is viewed as a time-varying system with time-dependent complexity.

2 DECOMPOSITION OF A SINGLE CUTTING OPERATION

Conventional metal cutting processes create the desired geometry by removing material from a solid workpiece. This involves clamping a tool and the workpiece, positioning the tool relative to the surface to be machined, and placing the tool in contact with the workpiece at high speed. For a single cut, the functional requirements of a conventional milling operation can be summarized as follows:

FR1 – Fix the workpiece (resist machining forces)
FR2 – Fix the tool (resist reaction forces)
FR3 – Position the tool relative to the workpiece
    FR31 – Position the tool (or part) in **x**
    FR32 – Position the tool (or part) in **y**
    FR33 – Position the tool (or part) in **z**
FR4 – Remove material
    FR41 – Cut (penetrate) the material surface
    FR42 – Separate material from surface (form the chip)
    FR43 – Break the chip
    FR44 – Remove the chip

Turning operations and 5-axis milling also require some or all of the rotational degrees of freedom of the tool to be defined relative to the workpiece. In this decomposition, the FRs associated with rotational positioning have been excluded for simplicity.

For many milling operations, workpieces are clamped in a vise. A tool chuck or collet assembly is used to clamp the tool. The part is positioned by moving the bed in x and y and by moving the quill in z. Material is removed by rotating the tool at high speed. The nature of the cut is dictated by the tool geometry (as well as the tool and workpiece material properties). Thus, the associated design parameters of a conventional milling operation for a single cut could include:

DP1 – Machine vise
DP2 – Tool chuck / collet assembly
DP3 – Positioning system
    DP31 – CNC controlled slide (x direction)
    DP32 – CNC controlled slide (y direction)
    DP33 – CNC controlled quill (z direction)
DP4 – Tool geometry
    DP41 – Lead angle
    DP42 – Rake angle
    DP43 – Rake face geometry
    DP44 – Flute geometry (helix angle)
DP5– Tool rotation (spindle speed)

The initial penetration of the tool into the workpiece (FR41) depends on the geometry at the tool tip and the tool rotation speed (DP41, DP42 and DP5). Similarly, chip formation (FR42) is controlled by the tool geometry and the tool rotation (DP41, DP42, DP43, and DP5). Chip breaking (FR43) depends on the curvature of the chip, the chip thickness, and the brittleness of the workpiece [Shaw, 2004]. As a result, chip breaking is highly coupled with chip formation and shares the same dependencies in the design matrix. If the flute geometry affects the chip curl or if the interaction of the flutes with the chips causes them to break, then FR43 will also be associated with DP44. Only chip removal (FR44) is relatively uncoupled – relying primarily on the flute geometry and the tool rotation (DP44 and DP5).

All cutting operations require the tool to slightly overlap the physical bounds of the workpiece. This overlap defines the depth of cut which, in turn, affects the cutting forces and chip formation. As a result, the initial penetration, chip formation, and chip breaking (FR41-FR43) all depend on the position of the tool (FR3). This is reflected in the high degree of coupling shown in the lower half of the design matrix (figure 1).

Finally, each cut involves the transmission of forces and moments from the tool to the workpiece. Reaction forces propagate from the tool through the tool chuck and the positioning system, and into the machine frame. Similarly, reaction forces propagate from the workpiece through the vise and into the machine frame. Because all physical components of the system are connected, errors in one machine element can impact other seemingly independent functions. For example, low stiffness or backlash in the positioning system can significantly change the position of the tool, induce vibration, and increase the cutting forces. This increases the reaction forces in the vise and the tool chuck and thus impacts their functionality. The result is a design matrix that is almost completely coupled.

Vargas *et al.* [2011] suggested additional design parameters (tool length/width ratio and tool material) to ensure that the tool can withstand the cutting forces. Similar requirements could also be defined for the vise, the tool chuck, the positioning system, and the machine frame. These design parameters can reduce the deflections caused by the transmission of forces but cannot eliminate them completely. This analysis neglects these considerations for simplicity.

$$\begin{pmatrix} FR1 \\ FR2 \\ FR3 \\ FR31 \\ FR32 \\ FR33 \\ FR4 \\ FR41 \\ FR42 \\ FR43 \\ FR44 \end{pmatrix} = \left[\begin{array}{cccccccccccc} X & X & X & X & X & X & X & X & X & X & 0 & X \\ X & X & X & X & X & X & X & X & X & X & 0 & X \\ X & X & X & & & & X & X & X & X & 0 & X \\ X & X & & X & 0 & 0 & X & X & X & X & 0 & X \\ X & X & & 0 & X & 0 & X & X & X & X & 0 & X \\ X & X & & 0 & 0 & X & X & X & X & X & 0 & X \\ X & X & X & X & X & X & X & & & & & X \\ X & X & X & X & X & X & & X & X & 0 & 0 & X \\ X & X & X & X & X & X & & X & X & X & 0 & X \\ X & X & X & X & X & X & & X & X & X & X & X \\ 0 & 0 & 0 & 0 & 0 & 0 & & 0 & 0 & 0 & X & X \end{array}\right] \begin{pmatrix} DP1 \\ DP2 \\ DP3 \\ DP31 \\ DP32 \\ DP33 \\ DP4 \\ DP41 \\ DP42 \\ DP43 \\ DP44 \\ DP5 \end{pmatrix}$$

Figure 1. Upper level design matrix for a single cutting operation on a vertical mill.

3 DECOMPOSITION OF SELECTED ADDITIVE MANUFACTURING PROCESSES FOR A SINGLE VOXEL

Additive manufacturing processes create the desired geometry by adding, solidifying, or fusing source material (filament, powder, sheet stock, etc.) until the desired shape has been produced.

3.1 FUSED DEPOSITION MODELING

Fused deposition modeling (FDM) processes create the desired geometry by positioning a nozzle, extruding new material, and bonding the new material to the existing bulk (or the build plate). The newly deposited material is separated from the nozzle by the shear forces generated by the movement of the nozzle away from the print location. The FRs for creating a generic FDM voxel (i.e. for the extrusion of a unit volume of material at a single location) can be summarized as:

FR1 – Position the nozzle aperture relative to the workpiece
    FR11 – Position the aperture in x
    FR12 – Position the aperture in y
    FR13 – Position the aperture in z
FR2 – Extrude new material
    FR21 – Heat material to glass-transition temperature
    FR22 – Advance material
    FR23 – Shape heated material
FR3 – Fuse new material to existing bulk
FR4 – Detach new material from source filament

If there is a need to orient the nozzle at an angle related to the workpiece, the rotational position of the nozzle would also need to be defined. Again, the FRs and DPs associated with rotational positioning been excluded from the decomposition for simplicity.

Most FDM machines either mount the nozzle on a three-axis gantry that moves relative to a stationary workpiece or mount the nozzle on a two-axis gantry and move the build plate in z to create each new layer. A heater softens the source material and an actuator is used to advance the filament and thus extrude the heated material. The nozzle shapes the heated material as it is extruded. Finally, the residual heat in the newly extruded material fuses the new voxel to the existing bulk. Thus, the DPs for creating a voxel using FDM could include:

DP1 – Positioning system
    DP11 – CNC controlled stage (x direction)
    DP12 – CNC controlled stage (y direction)
    DP13 – CNC controlled stage (z direction)
DP2 – Extrusion system
    DP21 – Resistive heater
    DP22 – Motor driven sprocket with filament guide
    DP23 – Nozzle geometry

It could be argued that DP3 should be defined as the bonding temperature at the new voxel interface. However, the temperature of the newly deposited material is directly controlled by DP21 (the heater). Similarly, it could be argued that DP4 should be the shear forces created by the movement of the nozzle away from the interface. However, the shear forces are created by the adhesion of the new voxel on one side and the movement of the nozzle (DP1 and its sub-DPs) on the other. As a result, the decomposition only has 2 DPs for 4 FRs. The resulting design matrix is rectangular and coupled (figure 2).

$$\begin{pmatrix} \text{FR1} \\ \text{FR11} \\ \text{FR12} \\ \text{FR13} \\ \text{FR2} \\ \text{FR21} \\ \text{FR22} \\ \text{FR23} \\ \text{FR3} \\ \text{FR4} \end{pmatrix} = \begin{array}{|c|c|c|c|c|c|c|c|} \hline X & & & & 0 & 0 & 0 & 0 \\ \hline & X & 0 & 0 & 0 & 0 & 0 & 0 \\ \hline & 0 & X & 0 & 0 & 0 & 0 & 0 \\ \hline & 0 & 0 & X & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & X & & & \\ \hline 0 & 0 & 0 & 0 & & X & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & & X & X & 0 \\ \hline 0 & 0 & 0 & 0 & & X & X & X \\ \hline 0 & 0 & 0 & 0 & X & X & 0 & 0 \\ \hline X & X & X & X & X & X & 0 & X \\ \hline \end{array} \begin{pmatrix} \text{DP1} \\ \text{DP11} \\ \text{DP12} \\ \text{DP13} \\ \text{DP2} \\ \text{DP21} \\ \text{DP22} \\ \text{DP23} \end{pmatrix}$$

Figure 2. Design matrix for an FDM process.

3.2 SELECTIVE SINTERING PROCESSES

Selective sintering processes (selective laser sintering (SLS), selective heat sintering (SHS), etc.) start with the bulk material as a powder on the print platform. To create a new voxel, a heat source is positioned over the desired area at an appropriate offset in the z direction and activated. The incident heat sinters the power and bonds the new material to the surrounding bulk. For a single voxel, the FRs for a selective sintering process are:

FR1 – Position the heat source relative to the workpiece
    FR11 – Position the heat source in x
    FR12 – Position the heat source in y
    FR13 – Position the heat source in z
FR2 – Sinter material into new voxel
FR3 – Bond new voxel to the existing bulk

The corresponding DPs for selective sintering are:

DP1 – Positioning system
    DP11 – CNC controlled stage for heat source (x direction)
    DP12 – CNC controlled stage for heat source (y direction)
    DP13 – CNC controlled stage for build platform (z direction)
DP2 – Heat source

New voxels are bonded to their neighbors (FR3) by the same thermal process that sinters them (FR2). This process requires a sufficient overlap between the old and new material to ensure that the bond is strong. Thus, FR3 is dependent on FR11, FR12, and FR2. In addition, the energy output of a heat source often depends on the distance to the material being heated. Thus, FR2 and FR3 both depend on FR13. The resulting design matrix is rectangular and coupled (figure 3).

$$\begin{pmatrix} \text{FR1} \\ \text{FR11} \\ \text{FR12} \\ \text{FR13} \\ \text{FR2} \\ \text{FR3} \end{pmatrix} = \begin{array}{|c|c|c|c|c|} \hline X & & & & 0 \\ \hline & X & 0 & 0 & 0 \\ \hline & 0 & X & 0 & 0 \\ \hline & 0 & 0 & X & 0 \\ \hline 0 & 0 & 0 & X & X \\ \hline X & X & X & X & X \\ \hline \end{array} \begin{pmatrix} \text{DP1} \\ \text{DP11} \\ \text{DP12} \\ \text{DP13} \\ \text{DP2} \end{pmatrix}$$

Figure 3. Design matrix for a selective sintering process.

3.3 STEREOLITHOGRAPHY AND 3D PRINTING PROCESSES

The decomposition and design matrix for light polymerised processes (e.g. stereolithography) are essentially the same except the starting material is liquid photopolymer instead of powder and DP2 is a light source instead of a heat source. This is a higher level design matrix than the one presented by Lee *et al.* [2004; 2007] and differs substantially from their work.

The decomposition and design matrix for 3D printing (binder jetting) processes are also the same except that a chemical binder is used instead of a thermal one. Thus, the heat or light source must be replaced with a droplet dispensing mechanism.

4 A COMPARISON OF REAL COMPLEXITY IN ADDITIVE AND SUBSTRACTIVE MANUFACTURING PROCESSES FOR INDIVIDUAL VOXELS

The decompositions above show that both additive and subtractive manufacturing processes are coupled on a voxel-by-voxel basis. However, the nature of the coupling in these systems is very different. Machining processes are highly coupled because of the forces and moments generated by the contact of the tool with the workpiece and the complex nature of the interaction of the tool with the part. Additive manufacturing processes have low contact forces (FDM) or no contact with the workpiece (SLS, SHS, stereolithography, 3D printing, etc.). As a result, additive manufacturing processes are not coupled through the positioning system. This partially explains why these systems are easier and less expensive to build, optimize, and control.

However, because additive manufacturing systems create and join individual voxels using the same mechanism, these two functions cannot be controlled independently. This results in less control over the geometry of the voxels and may partially explain why most additive manufacturing processes still produce parts that are "near net shape" [Levy *et al.*, 2003] while machining operations can be extremely precise.

5 TIME DEPENDENCE IN SUBTRACTIVE MACHINING OPERATIONS

While the analysis of conventional machining operations at the voxel level provides insight into the coupling and real complexity of these processes, machining is a time-dependent operation in practice. For example, end mills repeatedly make and break contact with the workpiece many times per second. Thus, milling can be viewed as a series of cuts and advancements along a desired tool path. In contrast, lathe tools rarely leave the surface. Thus, turning can be viewed as a process of uninterrupted cutting and advancement along the desired tool path.

For both milling and turning, the time between cuts and advancements is small (or non-existent). As a result, heat is constantly generated by the friction between the workpiece and the tool, leading to an increased temperature at the interface. Cut material can build up on the edge of the tool, the tool can wear down, and the interaction of the tool and the workpiece leads to vibration in the machine frame. From this perspective, machining processes exhibit significant time-dependent complexity.

One strategy to compensate for these effects is to use periodicity. For example, tools are regularly resurfaced or replaced to remove the built up edge and compensate for tool wear. A similar strategy could be used to manage the temperature increase at the tool / workpiece. For example, one could increase the amount of time between cuts to allow the tool and the workpiece to cool naturally. However, this greatly increases processing time. Instead, one additional functional requirement and one additional DP are used to compensate for the transient thermal behaviour:

FR5 – Control the temperature at the interface between the tool and the workpiece

DP6 – Apply lubricant / coolant to the interface

The application of the lubricant / coolant is independent of the other FRs and DPs. However, the quality and geometry of the cut depends on the frictional behavior at the interface. Thus, all aspects of the process, except for chip removal, depend on DP6 (figure 4).

$$
\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR31 \\ FR32 \\ FR33 \\ FR4 \\ FR41 \\ FR42 \\ FR43 \\ FR44 \\ FR5 \end{Bmatrix}
=
\begin{bmatrix}
X & X & X & X & X & X & X & X & X & X & 0 & X & X \\
X & X & X & X & X & X & X & X & X & X & 0 & X & X \\
X & X & X & & & & X & X & X & X & 0 & X & X \\
X & X & & X & 0 & 0 & X & X & X & X & 0 & X & X \\
X & X & & 0 & X & 0 & X & X & X & X & 0 & X & X \\
X & X & & 0 & 0 & X & X & X & X & X & 0 & X & X \\
X & X & X & X & X & X & X & & & & & X & X \\
X & X & X & X & X & X & & X & X & 0 & 0 & X & X \\
X & X & X & X & X & X & & X & X & X & 0 & X & X \\
X & X & X & X & X & X & & X & X & X & X & X & X \\
0 & 0 & 0 & 0 & 0 & 0 & & 0 & 0 & 0 & X & X & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X
\end{bmatrix}
\begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP31 \\ DP32 \\ DP33 \\ DP4 \\ DP41 \\ DP42 \\ DP43 \\ DP44 \\ DP5 \\ DP6 \end{Bmatrix}
$$

Figure 4. Design matrix for machining operations on a vertical mill.

6 TIME DEPENDENCE IN ADDITIVE MANUFACTURING PROCESSES

Most additive manufacturing processes are also more accurately modeled as continuous operations. For example, FDM machines continuously extrude material along a tool path instead of printing individual voxels. Similarly, SLS and SHS processes do not sinter the powder source material for contiguous features one voxel at a time. Instead, the heat source usually moves at a constant velocity, sintering along the pre-defined tool path. The dynamic nature of these processes can introduce significant time-dependent complexity.

6.1 THERMALLY-BASED TIME-DEPENDENT COMPLEXITY IN FDM

In FDM processes, the constant addition of new material introduces complex thermal transients that are difficult to predict. For example, the material at the beginning of the first strand of a build using a single nozzle machine will have warm material behind it, the build plate at ambient temperature below it (if unheated), and air at ambient temperature on the other four sides. The material in the second row will have material from the first row on one side. The temperature of the adjoining material will depend on how long it has had to cool, which depends on the length of the previous strand. Similarly, the strands in the layers above will have material below whose temperature will also depend on how long it had to cool and to what extent it has been warmed and/or insulated by the surrounding build. As the workpiece is created, the air surrounding the extruded material may develop temperature gradients that affect and further complicate the cooling process.

The thermal gradients in the workpiece are important because the heating and cooling of the extruded material play a substantial role in determining the final material properties and the geometry of the part. For example, the bonding process, and thus the bond strength, between the old and new material depends, in part, on the temperature difference between them [Li *et al.*, 2002]. Insufficient bonding can lead to reduced strength of the overall part and peeling or internal de-bonding.

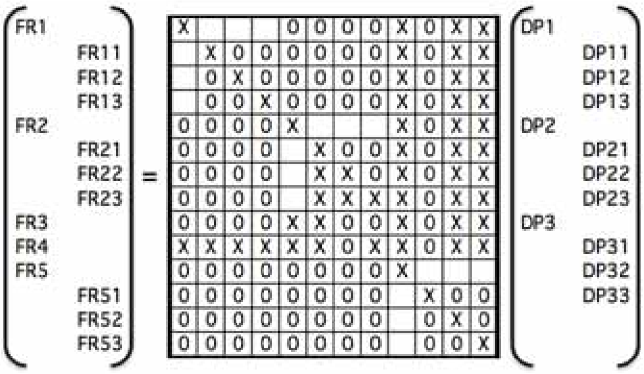
Thermal gradients can also affect the geometry of the final part. For example, temperature differences in the workpiece can lead to thermal stresses that cause warping in the final part [Wang *et al.*, 2007]. Differences in thermal expansion can generate internal voids and other dimensional errors after the part cools. Finally, the workpiece is subject to gravitational loads during construction. Materials, especially polymers, are relatively weak when warm. As a result, the bottom layers of a large workpiece may deform under the weight of the new material, altering the geometry of the final part.

Adding new functions associated with temperature control can mitigate some of these problems. For example, some FDM machines have heated build chambers. This leads to one new FR/DP pair:

FR5a – Maintain workpiece temperature slightly below glass transition temperature
  FR51a – Measure the temperature in build chamber
  FR52a – Add thermal energy to build chamber
  FR53a – Distribute thermal energy evenly throughout the build chamber

DP3a – Thermal management system
  DP31b – Temperature sensor
  DP32b – Heater
  DP33b – Fan

The new FR/DP pair is uncoupled (as long as the influence of the control system is not considered). However, a heated build chamber can introduce thermal expansion effects in the positioning system (FR1), the filament advancement mechanism (FR22), and the extrusion nozzle (FR23). Thus, these FRs are coupled through the new DP. In addition, the filament heater output will need to be adjusted to compensate for the higher build chamber temperature (FR21). The fusing of the new material (FR3) and the shearing of the source material (FR4) are also temperature dependent. Thus, the introduction of a heated build chamber reduces thermal time-dependent complexity in the part (and part quality) while increasing the overall coupling and complexity of the system (figure 5).



FR1	X				O	O	O	O	X	O	X	X	DP1
FR11		X	O	O	O	O	O	O	X	O	X	X	DP11
FR12		O	X	O	O	O	O	O	X	O	X	X	DP12
FR13		O	O	X	O	O	O	O	X	O	X	X	DP13
FR2	O	O	O	O	X				X	O	X	X	DP2
FR21	O	O	O	O		X	O	O	X	O	X	X	DP21
FR22	O	O	O	O		X	X	O	X	O	X	X	DP22
FR23	O	O	O	O		X	X	X	X	O	X	X	DP23
FR3	O	O	O	O	X	X	O	O	X	O	X	X	DP3
FR4	X	X	X	X	X	X	O	X	X	O	X	X	DP31
FR5	O	O	O	O	O	O	O	O	X				DP32
FR51	O	O	O	O	O	O	O	O		X	O	O	DP33
FR52	O	O	O	O	O	O	O	O		O	X	O	
FR53	O	O	O	O	O	O	O	O		O	O	X	

Figure 5. Design matrix for an FDM process with a heated build chamber.

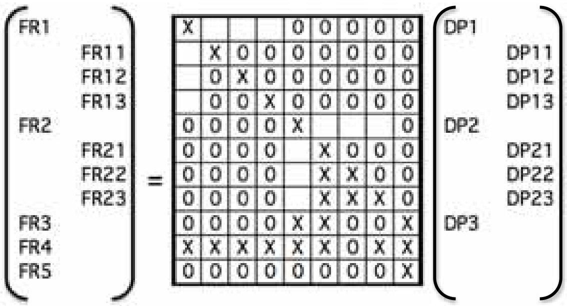
While heated build chambers have been shown to reduce warping in ABS parts produced by FDM, it is a global solution to a local problem. Heating the build chamber does not control the temperature gradients in the workpiece or the print bed. It only reduces the difference between the ambient temperature and the newly printed or sintered material, lessening the difference's effects.

Another common solution is to heat only the build plate. In this case, the FR/DP pair is defined as:

FR5b – Maintain workpiece temperature slightly below glass transition temperature

DP3b – Build plate resistance heater

Since the surrounding air will not be heated (except by the workpiece), a heated build plate will lead to higher thermal gradients than a heated build chamber, and thus greater time-dependent complexity. However, the overall coupling in the design matrix is lower because the positioning and extruding elements of the machine are unaffected by the build plate temperature (figure 6).



FR1	X				O	O	O	O	O	DP1
FR11		X	O	O	O	O	O	O	O	DP11
FR12		O	X	O	O	O	O	O	O	DP12
FR13		O	O	X	O	O	O	O	O	DP13
FR2	O	O	O	O	X				O	DP2
FR21	O	O	O	O		X	O	O	O	DP21
FR22	O	O	O	O		X	X	O	O	DP22
FR23	O	O	O	O		X	X	X	O	DP23
FR3	O	O	O	O	X	X	O	O	X	DP3
FR4	X	X	X	X	X	X	O	X	X	
FR5	O	O	O	O	O	O	O	O	X	

Figure 6. Design matrix for an FDM process with a heated build plate.

In both cases, increasing the overall temperature of the workpiece during the build does not improve, and may actually worsen, the effect of gravity on the lowest layers of the build.

6.2 THERMALLY-BASED TIME-DEPENDENT COMPLEXITY IN SINTERING PROCESSES

Thermal transients and thermally-based time-dependent complexity also exist in sintering processes. The first voxel in a sintered process will be surrounded on four sides by powder at ambient temperature and by air on the top. The second voxel will have warm sintered material behind it, powder on three sides, and air on the top. The heat from the newly sintered material is transmitted into the powder bed, which then develops thermal gradients [Dressler *et al.,* 2010] and affects the cooling of the workpiece. The air above the print bed will also be heated. As new layers of powder are added, they may trap the heat in the print bed and/or be heated by the workpiece in the print bed. The exact behavior will depend on the densities and thermal properties of the materials involved. The result is a temperature profile in the workpiece, in the print bed, and in the air above the print bed, that is difficult to predict and control.

Thermal gradients in selective sintering processes can lead to residual stresses in the final part like those observed in FDM. Since the heat required for bonding is applied directly to both the new voxel and to the surrounding material, thermal gradients have a much smaller effect on the bonding process. However, the heat will continue to diffuse through the bulk. Thus, the movement of the heat source will make and re-make the internal boundaries of the workpiece. This can have a substantial impact on the microstructure and thus material properties of the final part.

6.3 GEOMETRICALLY-BASED TIME-DEPENDENT COMPLEXITY

In all additive manufacturing processes, the workpiece must be able to support the layers that have been, or will be, created on top of it. Voxels cannot be placed without support and the weight of the voxels in higher layers must be taken into account when creating the lower layers. Sometimes this means that the part must be created in an orientation that will provide the necessary support during the manufacturing process. This makes many additive manufacturing processes path dependent.

To reduce the path dependence and increase geometric freedom, many additive manufacturing processes have additional FRs and DPs to provide mechanical support during the build. For example, many FDM machines print support material to allow over-hangs to be created. 3D printing and selective sintering processes use the un-sintered or un-bonded powder to provide this support. However, there are added constraints associated with this geometric freedom. The support layers must be removable using a mechanical or chemical process that does not affect the newly created structure. There also must be a path to allow the support material to be removed [Levy *et al.,* 2003; Vayre *et al.,* 2012] or the support material must be permitted to stay in the finished part.

7 SUMMARY AND CONCLUSION

This work has examined traditional subtractive machining processes and some of the major additive manufacturing processes from the perspectives of Axiomatic Design Theory and Complexity Theory. It was shown that subtractive processes exhibit more coupling within the design matrix than additive manufacturing processes. However, additive processes tend to have rectangular design matrices, with more FRs than DPs, and are thus inherently coupled. The additive manufacturing processes also seem to exhibit more time-dependent complexity than their subtractive counterparts. This analysis fails to support the hypothesis that additive manufacturing processes are inherently less coupled than subtractive manufacturing processes. However, it does provide some insight into the differences between the two types of processes and highlights sources of coupling to be addressed in future work.

8 ACKNOWLEDGEMENTS

The authors would like to thank Prof. Hans Nørgaard Hansen and Dr. David Bue Pedersen for their comments and discussion about this work.

9 REFERENCES

[1] Dressler, M., Röllig, M., Schmidt, M., Maturilli, A., Helbert, J., "Temperature distribution in powder beds during 3D printing." *Rapid Prototyping Journal*, 16, (5), pp.328 – 336, 2010.

[2] Lee, S.-J., Lee, I.H., Cho, D.-W., Hwang, W., "Design for Micro Stereolithography using Axiomatic Approach." *Proceedings of the 3rd International Conference on Axiomatic Design*, 2004.

[3] Lee, S.-J., Kang, H.-W., Kang, T-.Y., Kim, B., Lim, G., Rhie, J.-W., Cho, D.-W., "Development of a scaffold fabrication system using an axiomatic approach." *J. Micromech. Microeng.* 17, pp. 147–153, 2007.

[4] Levy, G.N., Schindel, R., Kruth, J.P., ""Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives." *CIRP Annals-Manufacturing Technology* 52(2), pp. 589-609, 2003.

[5] Li, L., Sun, Q., Bellehumeur, C., Gu, P., "Investigation of bond formation in FDM process." In *Solid Freeform Fabrication Symp.*, Austin, TX, pp. 1-8, 2002.

[6] Markillie, P., "A Third Industrial Revolution: Special Report Manufacturing and Innovation" *Economist Newspaper*, 2012.

[7] Mishra, S., "Helping additive manufacturing 'learn'." *Metal Powder Report*, 68(4), 38-39, 2013.

[8] Shaw, M.C., *Metal Cutting Principles,* New York: Oxford University Press, 2004.

[9] Suh N.P., *Axiomatic Design: Advances and Applications*, Oxford University Press, 2001.

[10] Suh, N.P., *Complexity: Theory and Applications.* Oxford University Press, 2005.

[11] Suh N.P., *The Principles of Design*, New York: Oxford University Press, 1990.

[12] Tucker, R., "Embracing 3D printing." *Metal Powder Report*, 68(2), 3, 2013.

[13] Vargas, A.V., Berger, U., Hansen, H.N., "Design of an Integrated Process Chain to Manufacture Titanium Components with Micro Features." *Proceedings of the 21st CIRP Design Conference,* pp. 37-45, 2011.

[14] Vayre, B., Vignat, F., Villeneuve, F., "Designing for additive manufacturing." *Procedia CIRP*, 3, pp. 632-637, 2012.

[15] Wang, T.M., Xi, J.T., Jin, Y., "A model research for prototype warp deformation in the FDM process." *The International Journal of Advanced Manufacturing Technology*, *33* (11-12), 1087-1096, 2007.